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Determination of Air Flotation Parameters to Perform Solid Liquid Separation Treatment in an Activated Sludge Treating Grease Waste by Promoting Filamentous Bacteria

Juan Guillermo Cartajena Torrealba
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Juan Guillermo Cartajena Torrealba entitled "Determination of Air Flotation Parameters to Perform Solid Liquid Separation Treatment in an Activated Sludge Treating Grease Waste by Promoting Filamentous Bacteria." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Civil Engineering.

Gregory D. Reed, Major Professor

We have read this thesis and recommend its acceptance:

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Accepted for the Council:
Dixie L. Thompson

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Interim Dean of Graduates Studies

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Determination of Air Flotation Parameters to Perform Solid Liquid Separation Treatment in an Activated Sludge Treating Grease Waste by Promoting Filamentous Bacteria

A Thesis Presented for
Master of Science
Degree

The University of Tennessee, Knoxville

Juan Guillermo Cartajena Torrealba
May 2007

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ABSTRACT

The focus of this investigation was the determination of air flotation parameters to perform solid liquid separation treatment in an activated sludge treating grease waste by promoting filamentous bacteria. The treatment was intended to achieve a pretreatment level, previous to the application of the typical activated sludge process.

Generally solid liquid separation in activated sludge is performed by gravitational settling, but it is been demonstrated that the presence of an overgrowth population of filamentous microorganism in activated sludges hinder the settling properties of it. For this reason, gravitational settling may result in an inefficient treatment. Therefore, an alternative treatment has to be applied.

The treated waste in this project has a density lighter than water; additionally filamentous microorganisms tend to trap fine bubbles therefore causes floating. These specific conditions make air flotation a suitable alternative technology. The ranges of minimum operation for Dissolve Air Flotation (DAF) controlling parameters (air pressure, recycle rate, rise rate, air to solid ratio, and solids recovery) were determined. For this purpose a descriptive model for the treatment was developed. The research determined that the traditional gravitational settling was not adequate for separating the biomass from the liquid phase. In contrast dissolve air flotation showed that it was possible to achieve the pretreatment level (300 mg/L in the final effluent).

In the analysis the correlations between the parameters under study (air pressure and recycle rate) and the response variables (rise rate, air to solid ratio, suspended solids in the subnatant, and solids recovery) were determined. With the relationships defined, the minimum ranges for the parameters of operation of a DAF unit were determined. The results showed that in order to achieve the pretreatment level air pressure should range between 45-70 psi and the recycle rate between 30-35%. All the values for the rest of the response variables were determined to be within the ranges of the typical application of DAF, therefore the same equipment used for the typical application can be used to apply this treatment under these specific conditions.

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CHAPTER I

INTRODUCTION

1. Introduction

The focus of this project is the determination of the air flotation control parameters for effective solid-liquid separation of an activated sludge rich in filamentous bacteria treating oil and grease wastewater. The project is based on a previous investigation (Seal et. al, 2006) in which design criteria for aerobic treatment of grease waste by promoting filamentous microorganisms in activated sludge were developed. Previous investigation results showed that the treatment did not achieve oil and grease concentrations low enough to be a final discharge. Therefore, this type of aerobic biological treatment would be suitable as a pretreatment only and the effluent would require final treatment in the normal treatment process at the wastewater treatment facility. For this reason, the present project determined the controlling parameters for air flotation to achieve an effective solids-liquid separation treatment at an acceptable pretreatment level.

Activated sludge processes are one the most frequently used biological processes to treat domestic sewage and industrial effluents. This process usually converts organic matter into energy for the organisms and a flocculent settleable biomass that can normally be removed by gravity sedimentation. However, common problems that can occur during this process when significant filamentous organisms are present, corresponding to foaming and bulking.

Overgrowth of filamentous microorganisms or organisms that can grow into a filamentous form, have been identified to be responsible of foaming and bulking. (Hong et. al. 1996). It is known that bulking sludges have poor settling characteristics and compactability. As a result, the removal of the biomass from the activated sludge is inefficient.

Filamentous bacteria tend to grow together in a net-like formation that hinders sludge settling and compaction and enhances the capture of gas bubbles. When the filamentous organisms grow above a determined level, they turn the flocs hydrophobic, allowing the attachment of air bubbles to the surface of the sludge (Jenkins et al 2003). Therefore, the solids present in the activated sludge tend to float.

This phenomena leads to the observation that a solid-liquid separation performed by air flotation should result in an effective removal process of the biomass present in this type of activated sludge.

1.1 Thesis Statement

This research will determine the values of operational control parameters involved in a solid-liquid separation performed by air flotation in an activated sludge rich in filamentous bacteria while treating an oil and grease wastewater.

1.2 Objectives

To support the research objective to calibrate the functional parameters of an air flotation unit to perform an effective removal of the biomass present in activated sludge treated by a biological process to deplete the oil and grease content, the specific objectives of the study are the followings:

1. Determine the ranges of operation of pressure and recirculation in an air flotation unit to perform an effective removal.

2. Determine the relation of the initial solid concentration and oil and grease content versus the effectiveness of the solid-liquid separation by air flotation.

3. Determine the minimum operating parameters to meet the pretreatment definition.

CHAPTER II

LITERATURE REVIEW

2. Literature Review

Several treatment options can be considered to achieve specific objectives in a treatment plant. The decision of which treatment will be the most effective is based on different factors which define the desired objective and will define the potential selection scenario.

The activated sludge process is the most widespread technology for wastewater purification. It is an aerobic biological process in which wastewater is treated with micro-organisms. It can be divided into two sections: the aeration phase and the solid-liquid separation phase. In the aeration phase the wastewater is contacted with an aerated mixed culture of microbes. During this contacting period the dissolved organics are removed and transported into the microbial cells. In the solid-liquid separation, the activated sludge is separated from the liquid, phase traditionally by sedimentation, and recycled to the aeration tank, in order to maintain a high concentration of biomass. The activated sludge will continue to build up until it is necessary to waste some of the excess. Solid-liquid separation occurs when a suitable environment is created in order to allow the activated sludge to flocculate and then be separated from the wastewater at the end of the biological treatment.

2.1 Solid-Liquid Separation

Solid-liquid separation is traditionally performed in an activated sludge process by gravity sedimentation. Sedimentation in an activated sludge process is caused by particles which are heavier than water. Particles present in the process are suspended by hydrodynamic forces. When the concentration of the particles is small, these particles tend to settle discretely, not being affected by the presence of other particles. Starting from rest, the velocity of settling of this discrete particle by gravity will increase, until the fluid resistance to flow through the liquid equals the effective weight of the particle. After this point the settling velocity will remain constant. The velocity in which the particle is settling is called *terminal settling velocity*. This phenomenon can be represented by the following equation:

$$v_t = \frac{gd^2(\rho_s - \rho_w)}{18\mu} \qquad \text{(Equation 2-1)}$$

Where,

v_t : terminal settling velocity

d : spherical diameter of the particle

g : gravitational acceleration

ρ_s : particle density

ρ_w : water density

μ : absolute dynamic viscosity of water

Equation 2-1 is basically a balance between the vertical forces acting while the particle is settling. This equation is applicable when the diameter of the particle is considered spherical and the particle is moving under laminar flow conditions. The particle will continue falling, as long as the density of the particle remains higher than the density of water.

There are many factors than can hinder the settling properties of the suspended particles, decreasing its efficiency. One of these factors is the presence of a big population of filamentous bacteria in the activated sludge. Filamentous bacteria directly affect the activated sludge settling properties. The main problems are filamentous bulking and foam, or scum problems. Filamentous microorganisms affect the floc density properties in the activated sludge, hindering the settling capacity. As a result, sedimentation is no longer a suitable treatment to perform a solid-liquid separation.

Filamentous bacteria directly affect the activated sludge settling properties. The main problems related with them are filamentous bulking and foam, or scum problems. Filamentous microorganisms affect the floc density properties in the activated sludge, hindering the settling capacity.

2.2 Filamentous Bulking

This phenomenon is the principal cause of poor compaction and settleability in activated sludges (Hong et. al, 1996). Filamentous bulking is mainly caused by an overgrowth population of filamentous organisms.

The filamentous organisms interfere directly with the settling and compaction of the activated sludge by growing in a large amount around the floc surface into the bulk solution and creating a net-like formation between them or producing a diffuse floc structure (Jenkins et. al, 2003). Figure 2-1 shows both cases observed under the microscope.

2.3 Foaming and Scum

Filamentous organisms are largely related with foaming and scum problems in activated sludge. The type of filamentous organisms related with foaming and scum are mainly nocardioforms, M. *parvicella* and, to a lesser degree, type 1863.

Nocardioforms and M. *parvicella* are filamentous organisms which possess a hydrophobic cell surface. This specific property is produced when these microorganisms grow in a large amount in an activated sludge. The flocs of this type are suitable for attachment of air bubbles on its surface. Then, the air bubble-floc aggregates are less

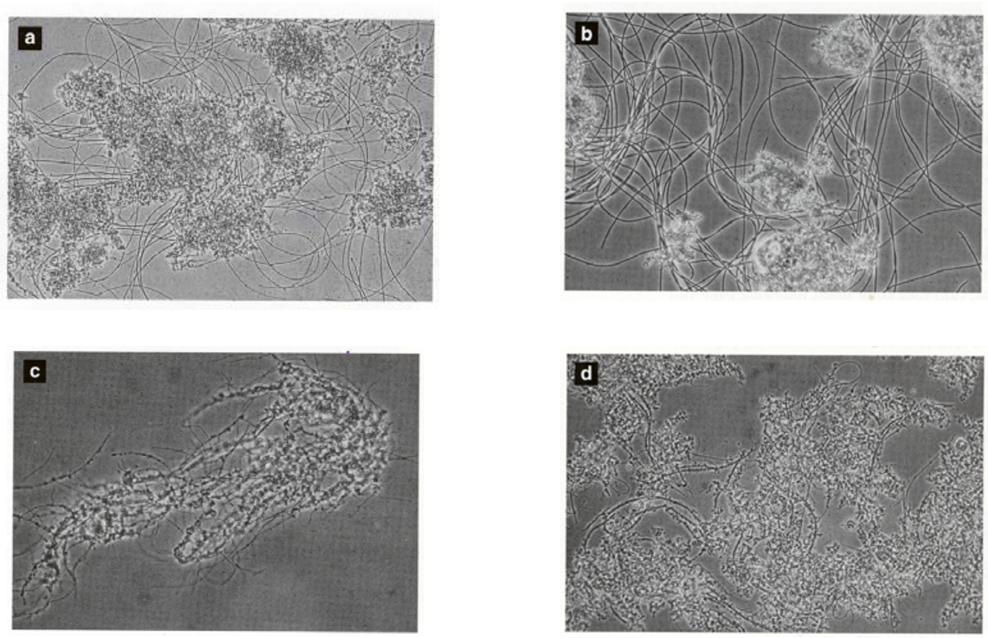


Figure 2-1 Phase contrast micrographs of effects of filamentous organism on floc morphology and settleability: (a) and (b) inter-floc bridging; (c) and (d) diffuse floc structure (Original magnification 100X)

Source: Jenkins et al., 2003

dense than water and, as a result, float to the surface forming a chocolate-brown colored float or scum (Jenkins et. al, 2003).

Nocardioform/M. *parvicella* scum can be identified by the following factors:

- Large, strong bubbles on the aeration basin.
- Higher levels of filamentous organisms in the scum compared to the mixed liquor.
- A greasy-looking surface film that forms during a settling test.

Depending on the type of filamentous organisms that are present in an activated sludge the settling interference caused by them will vary. Table 2-1 shows the different problems caused by filamentous organisms to solid separation in activated sludge.

Filamentous microorganisms typically appear when nutrients and air content problems are present in activated sludges. In order to check nutrient deficiency, levels of ammonia or nitrate and ortho-phosphate are tested. It is been tested that a low content of the nutrients mentioned is responsible of filamentous bulking. Since the inclusion of air, during the aeration phase, is part of the process of activated sludge, the amount of air release has to be control. A lack of oxygen in the aeration tank may affect the growth of filamentous bacteria.

Table 2-1 Compaction and Settling Interference Caused by Filamentous Organisms

Filamentous Organism	Bridging	Open Floc Structure
Haliscomenobacter hydrossis	Yes	Yes
Microthrix parvicella	No	Yes
Nostocoida limicola I and II	No	Yes
Nostocoida limicola III	Yes	No
Sphaerotilus Natans	Yes	No
Thiothrix I and II	Yes	No
Type 021N	Yes	No
Type 0041	Yes	Yes
Type 0092	No	Yes
Type 0581	No	Yes
Type 0675	No	Yes
Type 0803	Yes	No
Type 0914	Yes	Yes
Type 0961	Yes	No
Type 1701	Yes	Yes
Type 1851	Yes	Yes

Source: Jenkins et. al, 2003

2.4 Activated Sludge Floc

Most of problems with the activated sludge solids are related to the nature of the floc. Activated sludges are characterized by a wide range of particle size, including single bacteria with dimensions from 0.5 to 5 μm and large flocs than can reach sizes greater than 1 mm (1000 μm) (Jenkins et. al, 2003).

Activated sludge flocs are made up of biological microorganism, inorganic particles and organic particles. When filamentous microorganisms are present in activated sludges, net-like formations can be seen. Table 2-2 shows the typical problems related with filamentous microorganism in activated sludge solid separation.

2.5 Correlation Between Total Extended Filament Length (TELF) and Sludge Volume Index (SVI)

Early studies used the total extended filament length to demonstrate that the settling properties of an activated sludge could be related to the level of filamentous organisms present in it.

Pipes (1979) performed a study and found that at low filament numbers ($\leq 10^2$ filaments/mg VSS), the SVI was below 100 mL/g, while at high filament numbers ($> 10^2$ to 10^3 filaments/g VSS), the SVI increased significantly.

Table 2-2 Causes and Effects of Filamentous-Related Activated Sludge Solids Separation Problems

Problem	Cause of Problem	Effect of Problem
Filamentous Bulking	Large Amounts of filamentous microorganisms present bridge between the flocs or create diffuse flocs, interfering with compaction, settling, and thickening.	High SVI with very clear supernatant; low RAS and WAS solids concentrations; in severe cases, the sludge blanket overflows the secondary clarifier; solids handling processes become hydraulically overloaded
Foam/Scum Formation	Caused by nocardioforms, M. *parvicella* or type 1863	Nocardioforms and M. *parvicella* foams are persistent and difficult to break mechanically; foams accumulated can putrefy; foams can overflow tank freeboards

Source: Jenkins et. al, 2003

Studies performed by Sezgin et. al (1978), Palm et. al (1980), and Lee et. al (1982) found correlations between activated sludge settling (SVI, in this case) and TELF for laboratory scale activated sludge. The results indicated that SVI increased rapidly above 150 mL/g when the TEFL values increased above 10^7 μm/mL. Sezgin et. al, (1980) demonstrated that these relationships were valid for activated sludge taken from several full-scale plants. Results of those studies can be seen in Figure 2-2 and 2-3.

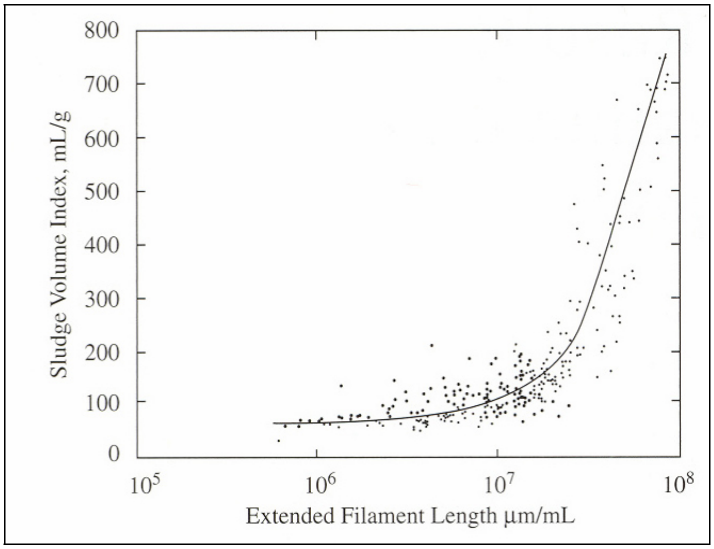


Figure 2-2 Effect of extended filament length on SVI

Source: Jenkins et. al, 2003

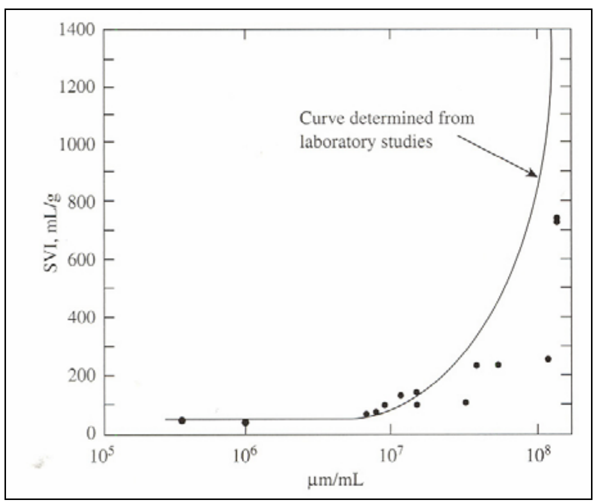


Figure 2-3 Variation of SVI with filament length for 14 full-scale California Wastewater Treatment Plants

Source: Jenkins et. al, 2003

2.6 Air Flotation

Since traditional gravitational solid-liquid separation cannot be performed given the problems caused by a high population of filamentous bacteria in the activated sludge, an alternative treatment has to be applied to separate the solids from the liquid. Because of the characteristics of the floc formation in this type of activated sludge, air flotation may offer a better solution for to this problem.

To accomplish a solid-liquid separation by air flotation, fine bubbles have to be generated. The bubbles will become associated with the sludge solids, increasing their buoyancy, and cause them float to the surface where they will be removed. All the concepts developed in the section 2.1 about sedimentation are completely applicable for air flotation. In this case the direction of the solids movement will be the opposite. In air flotation terms, the terminal settling velocity is called *rise rate*. The major difference between sedimentation and air flotation relies on the nature of the sludge which can be effectively thickened.

The effectiveness of the process mainly depends in how well the particles can be agglomerated with air bubbles in order to make them float to the surface. Various techniques can be applied to introduce the small air bubbles required to performed air flotation. One of these techniques corresponds to dissolved air flotation (DAF).

Dissolved air flotation consists in pressurize a recycle effluent which will be released to blend with the feeding influent. When the recycle effluent is pressurized, fine bubbles can be generated. The size of the bubble typically ranges between 10 to 100 μm in dissolved air flotation. To achieve maximum collision and attachment between air bubbles and the suspended particles, bubbles must rise under laminar flow conditions. This avoids shredding of floc, which can occur in a turbulent regime. The maximum bubble size for laminar flow is 130 μm (AWWA, 1999). The main factors involved in the DAF process are air pressure, recycle ratio, and air to solid ratio. The size of the bubbles is an important factor to achieve an efficient solid-liquid separation. Air pressure influences directly the size of the bubbles generated. If the size of the bubbles is too large, they do not attach to the particles, while a very fine bubble can form a very fragile floc. A bubble size less than 100 μm is commonly best. However, choosing the best bubble size has to be made by conducting several experiments at different pressures. There is a relationship between the bubble size and pressure. As the pressure applied to the recycle effluent gets higher, the size of the bubbles get smaller. Thus, starting from a low pressure value, different sizes (related to different air pressure values) will be tested, obtaining as a result the best bubble size for the specific scenario.

As mentioned above, the same concepts developed for sedimentation are applicable to dissolved air flotation. Rise rate correspond to the velocity in which the floc particle-bubble aggregate rise towards the surface. The expression to calculate rise rate is similar to the one for the terminal settling velocity.

$$v_b = \frac{g d_{pb}^{\ 2} (\rho_w - \rho_{pb})}{18\mu} \qquad (\textit{Equation 2-2})$$

Where,

v_b : rise velocity of the particle-bubble aggregate

d_{pb} : spherical diameter of the particle-bubble aggregate

g : gravitational acceleration

ρ_{pb} : particle-bubble aggregate density

ρ_w : water density

μ : absolute dynamic viscosity of water

As can be seen in the equation above, the basis of this treatment is similar to the one used for sedimentation, but now rise rate is based on the fact that the particle-bubble aggregate is less dense than water. In dissolved air flotation the lower the density of the particle-bubble aggregate with respect to water, the more likely it is that it will float. Dissolved air flotation increases the rate of separation of particles with a density slightly less than that of water.

In the specific case of an activated sludge rich in filamentous bacteria the tendency of them to growth in net formation, make the particles more likely to get attached to the air bubbles.

2.7 Factors Affecting the Performance of a Dissolve Air Flotation System

Numerous factors affect the dissolve air flotation process performance. The most important are explained in this section.

- Air pressure: as mentioned before, the size of the bubbles generated when the recycle effluent is pressurized depends directly on the operational pressure applied in the pressurized chamber. Typical operational values for air pressure range between 40-80 psi.

- Recycle Ratio: The recycle ratio is determined as the fraction of the final effluent produced which is returned and saturated under pressure prior to entering the flotation chamber where the pressure is subsequently released and the bubbles are generated. The recycle ratio can vary immensely with recycle ratios being typically 20-100% for water and wastewater treatment application. Air dissolution rates are proportional to absolute pressure (i.e. system gauge pressure + atmospheric pressure) in accordance with Henry' Law of partial pressures of gases adjacent to liquids. Thus, for a given application, the higher the operating pressure of the air/water saturation vessel, the lower the required percentage recycle – and vice-versa. High values of recycle ratio are typically avoided. The main reason to avoid them is because the higher the values for recycle ratio, the higher will be the amount of air (bubbles) released to the flotation tank. At high values of recycle ratio, the excess of bubbles will cause an excessive turbulence on the flow, which will break the connections of the particle-bubble aggregate, hindering the performance of the treatment.

- Air to Solid Ratio: air to solid ratio is possibly the most important factor affecting the DAF performance. It refers to the weight ratio of air available for flotation and the solids to be floated in the influent stream. Air to solid ratio is generally set up in order to minimize the amount of air needed to perform the solid-liquid separation, thus potential turbulence problems inside of the flotation tank can be avoided. If excessive turbulence occurs, shear forces acting on the surface of the particle-bubble aggregate will increase, breaking up its structure. As a consequence, the performance of the treatment will be hindered. This value has also a big influence in the final cost of the application of this treatment. The lower the value, less air will be needed to be released to the flotation chamber, resulting in a more economic treatment.

- Percentage of recovery: this parameter is a measure of the efficiency of solids recovery obtained at a fixed set of operating conditions. Several studies have reported recoveries of at least 95% in different plants. In order to prevent adverse effects on other unit processes when recycling the flotation subnatant, percentage of recovery of at least 95% is required. Percentage of recovery can be enhanced with the addition of polymers to the process. Solids recovery without polymer addition generally can be higher than 90% in most of the applications. High loadings or adverse solids conditions can decrease the percentage of solids recovery to 75% to 90%. With a polymer addition this value can be exceed 95%. The choice of the best polymer to apply will vary for each installation. However, lately the price of resins and polymers used to manufacture coagulants has been increasing very fast, turning this practice into a very expensive one. Values from the producer price index showed an increase of 50% for the price of resins and plastics between 2003 and 2005 (Zabilansky and LaMontagne, 2006). For these reason, this project was structured to seek acceptable operating parameters that did require polymers. Therefore, polymers were not applied in the determination of the minimum ranges required to achieve the pretreatment quality of the effluent.

Based on the information obtained from the literature, it can be implied that dissolved air flotation is a viable option to perform a solid-liquid separation in an activated sludge rich in filamentous bacteria. In the next chapters, an experiment for determining the air flotation parameters to perform a solid-liquid separation treatment in an activated sludge rich in filamentous bacteria treating an oil and grease waste is explained.

CHAPTER III

METHODOLOGY

3. General Information

As described in Chapter 2, the tendency of the filamentous bacteria to grow together in a net-like formation permits floc attachment to air bubbles. This specific formation makes the bubble-floc aggregates to be less dense than water, causing them to float to the surface.

Solid-liquid separation experiments were performed based on this phenomenon. As mention on the objectives of this project, solid-liquid separation was performed using a DAF.

This specialized treatment was intended to be a pre-treatment to be followed by treating the effluents in a conventional activated sludge plant. For this reason the acceptable effluent quality was set at a maximum of 300 (mg/L) of suspend solids.

3.1 Methodology

This section will be divided in two major parts: Procedure and Parameters Calculated.

3.1.1 Procedure

Samples of activated sludge were taken directly from a medium scale batch reactor. The reactor had a volume of one cubic meter, with an upper rigged structure that permitted the support of mixing equipment and the aeration system. The aeration system consisted of a shaft with a diffuser system located at the end, which was connected to a compressor by an air line. The degree of aeration was controlled by the use of a valve. Two mixers provided the mixing for the $1m^3$ reactor.

The reactor is located at Kuwahee Waste Treatment Plant, inside the DAF unit building. The reactor was constructed by the KUB from a $1m^3$ polymer tank and an upper rigging structure was installed for supporting the mixing motors and aeration system.

A biological treatment to deplete oil and grease, using filamentous bacteria, was being performed. Samples were taken from the bottom of the reactor by opening a valve located in one of the sides of it. In order to take the take the samples a 1 gal bucket was used.

Immediately after the sample was taken, the general properties and settling properties of the solids were measured. The following general properties were recorded: total solids and suspended solids of the activated sludge influent. These tests were performed following the procedures indicated in *Standard Methods* sections 2540.B, and 2540.D. In order to measure the settling properties of the sample, the sludge volume index (SVI) was calculated. The test was performed following the procedure indicated in *Standard Methods* section 2710.C.

A stirring mechanism was installed in the bucket to keep the sample well mixed and avoid a separation between the liquid and solid phases.

DAF test was performed using the following procedure:

Step 1

Different combinations of air pressure and recycle ratio were selected. The experiment consisted in a 3 by 3 factorial; therefore 9 different combinations were evaluated.
The ranges for air pressure and recycle ratio were 40-60 psi and 30-50 % respectively. The reasons for choosing these ranges are explained in Chapter 4.

Step 2

Recycle effluent was prepared. This recycle effluent consisted in an effluent with a Suspended Solid content lower than 300 (mg/L). DAF test procedure uses an effluent recycle method of aeration, which is basically recycle effluent being pressurized with air and release into a flotation cell.

Once recycle effluent was prepared, recycle rate of the effluent was calculated. Recycle rate corresponds to the ratio between the effluent being pressurized with air and the influent stream in the DAF unit (activated sludge). For example if the recycle rate applied in the test is 40%, that means:

$$1000(ml) * 0.40 = 400(ml)$$

The required volumes to test were:

Pressurized effluent = 400 ml

Activated Sludge = 600 ml

Step 3

The system was set up according with the instructions given in the Operation Manual for the Diffused Air - Dissolved Air Flotation Test Apparatus (DADAFTA) (OFI Testing Equipment, Inc., 2005).

Step 4

Preparation and DAF test procedure were performed according with the instructions given in the Operation Manual for the Diffused Air - Dissolved Air Flotation Test Apparatus (DADAFTA) published by OFITE, Inc., in step 4 and 5 respectively.

3.1.2 Method of Analysis

Once the data was collected, a statistical analysis was performed to determine the significant estimated parameters (i.e. air pressure, recycle ratio, and total solids in the raw sample) in the system. With the data collected, a prediction model was developed. In order to predict the efficiency of the treatment, correlations between the variables involved in the system were determined (based on the experimental data). Once the correlation equations were determined contour profilers were used to obtain the optimal ranges for the controlling parameters of air flotation.

To perform the statistical analysis and develop the prediction model, a statistical software package was used. The software selected for this purpose corresponded to JMP 6.0. JMP 6.0 is a powerful statistical tool which is able to developed prediction models based on experimental data, determining the correlation equations between the independent and dependent variables involved in the system. When relationships are determined, JMP can develop contour profile. Contour profiles are a graphical representation of the empirical equations determined. With them, limitations on the working ranges for each variable can be observed and analyzed. Fixing upper and lower limits for the dependent variables, JMP is useful to simulate certain scenario conditions for different types of treatments or weather conditions. As a result, JMP 6.0 was the most appropriate and user-friendly statistical tool to analyze the data of the present project.

3.1.3 Parameters Calculated

Once the test was performed, the height of the liquid-solid interface was recorded. Liquid-solid interface is where the bottom portion of the solids boundary meets the top portion of the dissolved air-fluid phase.

a) Rise Rate

At the beginning of DAF test, the solid-liquid interface is located at the bottom of the DAF unit chamber. As flotation started, the solid-liquid interface starts moving upwards.

The position of the interface was noted using the appropriate graduate (ml) along the flotation cell as a reference. Recording was performed for 15 minutes with intervals of 1 minute between every measurement. At times, the solids-liquid interface was vague. For this reason a good judgement had to be exercised in following the rate of rise of the interface.

The average slope was computed by adding the highest gain obtained between intervals and the lowest gain between lowest gain intervals, and then divided by 2. For converting the average slope to Rise Rate:

$$\text{Rise Rate} = \left(\frac{\frac{AverageSlope}{3725}}{0.06705} \right) (GPM / ft^2) \qquad \textit{(Equation 3-1)}$$

b) Total and Suspended Solid Content

After flotation was complete, total solids of the supernatant and total suspended solids of the subnatant were calculated. Tests were performed following the procedures in the *Standard Methods* in sections 2540.B and 2540.D respectively.

c) Percent Recovery (%R):

Using the values obtained for the total solids of the raw sludge, and the subnatant, percent recovery was calculated using the following equation:

$$\%R = \left[1 - \left(\frac{C_F}{C_O}\right)\right] * 100 \qquad \textit{(Equation 3-2)}$$

Where:

%R: Percent Solids Recovery

C_o: Total Solids in Raw Sludge Influent

C_F: Total Solid in Subnatant

This parameter represents the percentage in which the solids in the raw sludge influent were reduced at the end of the treatment.

d) Air-to-Solid Ratio

This represents one of the most important factors affecting the performance of a DAF unit. It expresses the ratio between the weight of air available to make the flotation possible to occur and the solids to be floated present in the influent stream.

Air-to-Solid Ratio corresponds to the following equation:

$$\frac{A}{S} = \frac{1.3 s_a (fP - 1)}{S_a} \qquad \textit{(Equation 3-3)}$$

Where:

A/S:	Air to Solids ratio, (ml/L)
s_a:	Air solubility, (ml/L)
f:	Fraction of Air Dissolved at pressure P, usually 0.5
P:	Pressure, (atm) (P+14.7)/14.7 (U.S. Customary Units)
S_a:	Sludge Solids, (mg/L)

3.2 Materials

The apparatus used to perform the DAF test correspond to the DADAFTA. Figure 3-1 and 3-2 shows a general scheme of a lab scale DAF unit.

DADAFTA unit consists of a clear, plastic housing (pressure cell), stainless steel stirrer, Lab Cock valve, Quick Disconnect "valved" Couplings – Barbed Mail, Chemical Inlet fitting w/septum, pressure release, o-ring, diffuser holder/nozzle, ceramic disc, pressure gage, Poly Pak Seals, Nylon – liquid – tight connector, tubing, 1 liter (1000 ml) plastic graduated cylinder (Flotation Chamber), pump, 2 pressure gauges, stainless steel support frame, tubing (1/16", 1/8", 3/16" ID) and threaded cap.

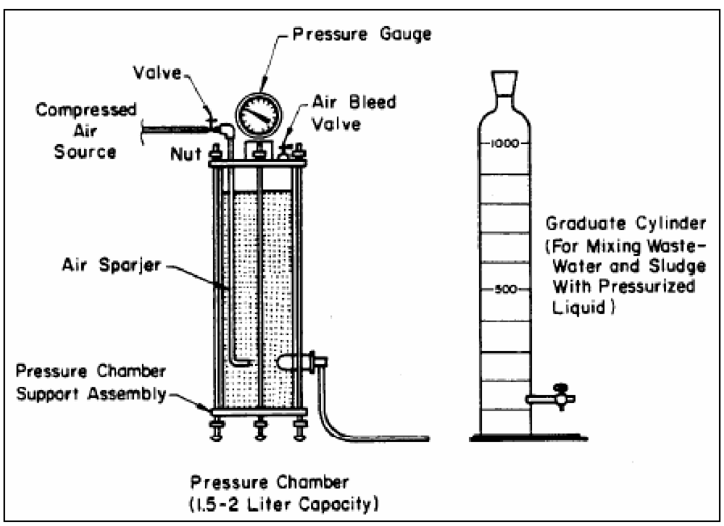


Figure 3-1 Lab Scale DAF unit

Source: OFI Testing Equipment, 2005

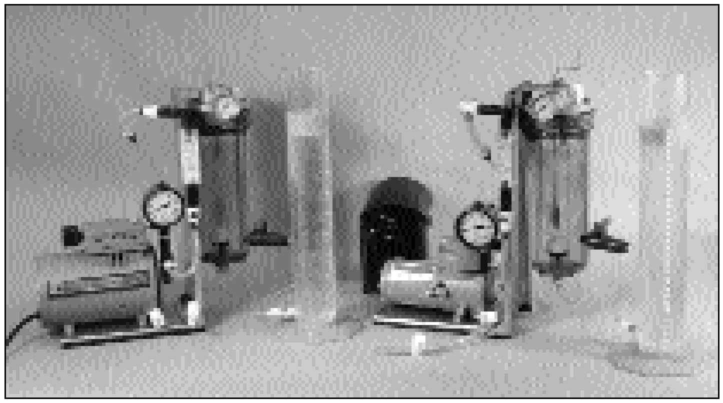


Figure 3-2 DADAFTA unit

Source: OFI Testing Equipment, 2005

CHAPTER IV

RESULTS AND DISCUSSION

4. Introduction

This chapter describes the analysis of the data collected for the study. The analysis was divided in two steps. The first one, focused in the analysis of the settling characteristics of the activated sludge, and the second one, focused in the analysis of the prediction model developed to determine the optimal ranges for the controlling parameters to perform the solid-liquid separation of a filamentous biomass in a DAF unit.

4.1 Settling Characteristics

Before performing the DAF test, once the sample was taken from the batch reactor, the Sludge Volume Index (SVI) was calculated. As it is mention in Chapter 2, it is known that there is a strong correlation between the TELF and SVI.

The settled sludge volume and SVI values of the samples collected in this study are shown in Table 4-1 and 4-2:

Table 4-1 Settled Sludge Volume

Sample	Time (min.)	Settled Volume (ml)
1	0	0
	5	0
	10	0
	15	5
	20	6
	25	16
	30	20
2	0	0
	5	3
	10	5
	15	10
	20	15
	25	33
	30	40
3	0	0
	5	0
	10	2
	15	5
	20	9
	25	16
	30	20
4	0	0
	5	5
	10	12
	15	15
	20	24
	25	44
	30	50

Table 4-2 Sludge Volume Index (SVI)

Sample	Settled Sludge Volume (mL/L)	Suspended Solids in Raw Sample (mg/L)	SVI (mL/g)
1	980	4206	233
2	960	4615	208
3	980	5000	196
4	950	4298	221

As it can be seen, values of SVI are all above 150 (mL/g), which is considered to be an acceptable value to perform dissolve air flotation. In a survey applied to expert engineers in different treatment plants, values for SVI were ranged between 100-150 mg/L when sedimentation was being applied (WEF, 1998). These values show that settling properties of the activated sludge are very poor, resulting in an inefficient performance. These values can be supported with the data shown in Figure 2-2, in which the values obtained on the tests, are associated with high values of TELF. Values for TELF are between 10^7 – 10^8 μm/mL.

Sezgin et. al. (1978) demonstrated that when values for TELF were above 10^7 μm/mL, SVI was increased rapidly above 150 mL/g. Figure 4-1 shows pictures taken using a microscope in which a high population of filamentous bacteria can be observed. Pictures were taken from a batch reactor in which an aerobic treatment of grease waste by filamentous bacteria was being performed (Seal, 2006)

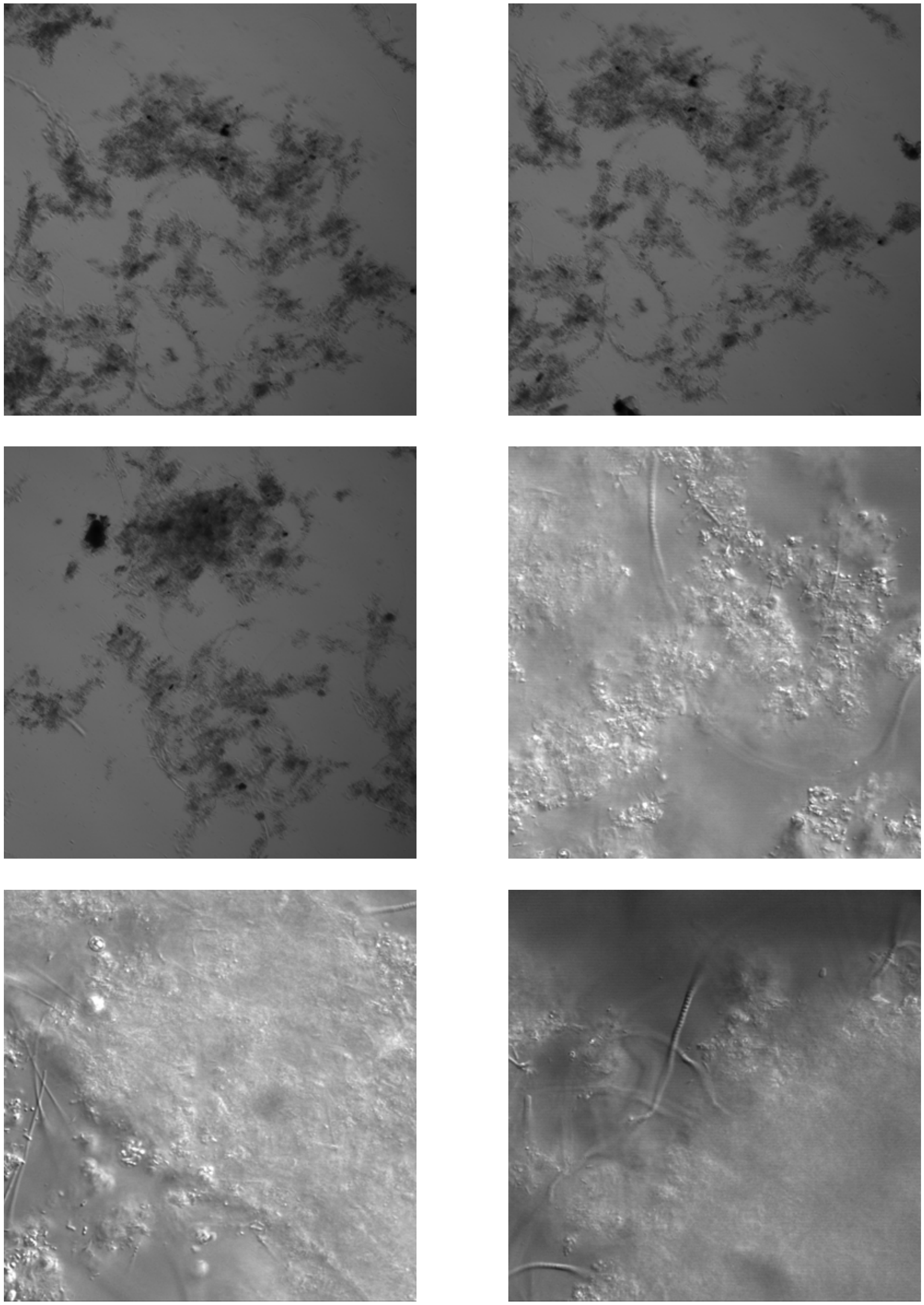


Figure 4-1 Microscope pictures of filamentous population in an activated sludge performing an aerobic treatment to treat grease waste (Seal, 2006)

4.2 Determination of Optimal Ranges for Controlling Parameters in DAF Unit

A statistical prediction model was used to determine the acceptable ranges for the controlling parameters to perform the desired level of solid-liquid separation. The variables involved in the statistical model are separated in two groups: *Variables Under Study*, and *Response Variables*.

a) Variables Under Study

- X1: correspond to the operation air pressure (psi).
- X2: recycle rate (%).
- X3: total solids of the raw sample (mg/L).

b) Response Variables

- Y1: total suspended solids in subnatant (mg/L).
- Y2: percentage of recovery (%R).
- Y3: air to solid ratio.
- Y4: rise rate.

The concepts and equations behind these parameters are explained in detail in Chapter 3, section 3.2.

Data was collected in a 3 by 3 factorial experiment; therefore, 9 combinations were possible. In order to perform the test, the method of randomization was used. This method consists of a random order to all the possible combinations, separating them in daily sessions. In this way, repetitive errors are minimized. Therefore, in every session, 9 runs of the DAF unit were performed; each of them with a different combination listed in a random order. In order to determine the optimal ranges of operation of the controlling parameters involved in the treatment, 4 sets of data were used. Table 4-3 shows the experimental data used to develop the prediction model and determine the correlations between the variables under study and the response variables.

4.3 Statistical Analysis of the Data

A non-linear second order model was fitted for each of the response variables. Using a second order model, linear and non-linear relationships could be observed.

In a previous investigation, a first attempt to determine the ranges of operation of a DAF unit was performed. Full ranges of operation for the parameters under study were evaluated, obtaining a first area of operation.

Fitting a response surface for the suspended solids in the subnatant (Y1), it was observed that the variance was proportional to the square mean (μ^2). Therefore it was transformed using Log (Y1).

Table 4-3 Experimental Data

Set	Pressure (Psi)	Recycle Ratio (%)	Initial Solids (mg/L)	Subnatant Solids (mg/L)	%R	A/S	Rise Rate
1	40	30	11960	140	98.8	0.5147	0.3
1	40	40	11960	415	96.5	0.6862	0.62
1	40	50	11960	280	97.7	0.8578	0.56
1	50	30	11960	124	99.0	0.7181	0.23
1	50	40	11960	480	96.0	0.9575	0.62
1	50	50	11960	306	97.4	1.1968	1.5
1	60	30	11960	80	99.3	0.9215	0.24
1	60	40	11960	423	96.5	1.2287	0.76
1	60	50	11960	358	97.0	1.5358	1.5
2	40	30	8740	340	96.1	0.7043	0.42
2	40	40	8740	489	94.4	0.939	0.51
2	40	50	8740	407	95.3	1.17378	0.52
2	50	30	8740	256	97.1	0.9826	0.37
2	50	40	8740	604	93.1	1.3102	0.54
2	50	50	8740	494	94.3	1.6377	1.03
2	60	30	8740	200	97.7	1.261	0.35
2	60	40	8740	546	93.8	1.6813	0.69
2	60	50	8740	578	93.4	2.1017	1.23
3	40	30	9120	258	97.2	0.6749	0.27
3	40	40	9120	412	95.5	0.8999	0.27
3	40	50	9120	305	96.7	1.1249	0.27
3	50	30	9120	195	97.9	0.9417	0.35
3	50	40	9120	498	94.5	1.2556	0.52
3	50	50	9120	367	96.0	1.5695	0.47
3	60	30	9120	168	98.2	1.2085	0.33
3	60	40	9120	447	95.1	1.6113	0.4
3	60	50	9120	406	95.5	2.0141	0.71
4	40	30	8250	284	96.6	0.6439	0.4
4	40	40	8250	312	96.2	0.8585	0.49
4	40	50	8250	285	96.5	1.0731	0.43
4	50	30	8250	260	96.8	0.8983	0.36
4	50	40	8250	343	95.8	1.1978	0.58
4	50	50	8250	387	95.3	1.4972	0.67
4	60	30	8250	245	97.0	1.1528	0.35
4	60	40	8250	398	95.2	1.5371	0.9
4	60	50	8250	446	94.6	1.9214	1.23

4.3.1 Results of Preliminary Investigation

The results obtained in a preliminary investigation are shown in the Tables 4-4, 4-5, 4-6, and 4-7. From the information shown in the Tables, the parameters of significance in the model and the ranges for operation parameters in a preliminary phase were determined.

From the previous results it is possible to observe from the summary of fit for every response variable that the RSquare value is higher than 0.89. This value indicates that data obtained will not need major corrections, thus the level of confidence on the analysis is high. In order to determine the parameters with the major influence on the behavior of the response variable results, parameters without a confidence higher or equal to 95% were screened out of the prediction model (Prob > 0.05). In Table 4-4, from the parameters estimated is possible to observe that the effluent suspended solid concentration (Y1) depended on the recycle rate (X2) (Prob = 0.0110) and the initial solids concentration (X3) (Prob = 0.0018). The initial suspended solids concentration it is hard to control, therefore the effluent quality will depend mainly from the recycling rate. Additionally, the percentage of solid recovery (Y2) (Table 4-5) depended on the recycle rate (X2) (Prob < 0.001), interaction between air pressure (X1), recycle rate (X2), and initial solids concentration (X3). Those interactions correspond to the terms X1X2, X2X2, X2X3 and X3X3, which represent the influence of those parameters acting together over the curve behavior defining the prediction equation for the response variable.

Table 4-4 Preliminary Investigation- Summary of Fit for Solids in the Subnatant (Log Y1)

Summary of Fit for Log (Y_1)

RSquare	0.890978
RSquare Adj	0.822838
Root Mean Square Error	0.199332
Mean of Response	5.630242
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	5.1954551	0.519546	13.0759
Error	16	0.6357302	0.039733	Prob > F
C. Total	26	5.8311853		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	4.7315742	1.277813	3.70	0.0019
X1	-0.00147	0.031745	-0.05	0.9636
X2	0.0271781	0.015457	1.76	0.0978
X3	-0.000033	0.000045	-0.73	0.4776
X1*X1	0.0001193	0.000229	0.52	0.6095
X1*X2	-0.000143	0.000118	-1.21	0.2444
X2*X2	-0.000131	0.000105	-1.24	0.2312
X1*X3	-2.614e-7	3.866e-7	-0.68	0.5086
X2*X3	-6.699e-7	2.332e-7	-2.87	0.0110
X3*X3	4.1925e-9	1.125e-9	3.73	0.0018

Table 4-5 Preliminary Investigation. Summary of Fit for Solids Recovery (Y2)

Summary of Fit for Y_2

RSquare	0.880874
RSquare Adj	0.80642
Root Mean Square Error	0.233786
Mean of Response	98.89481
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	6.4663819	0.646638	11.8311
Error	16	0.8744922	0.054656	Prob > F
C. Total	26	7.3408741		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	102.516	1.49868	68.40	<.0001
X1	-0.049575	0.037232	-1.33	0.2017
X2	-0.113697	0.018129	-6.27	<.0001
X3	0.0000961	0.000053	1.82	0.0874
X1*X1	0.0001377	0.000269	0.51	0.6153
X1*X2	0.0003983	0.000139	2.87	0.0111
X2*X2	0.0006173	0.000123	5.01	0.0001
X1*X3	4.6325e-7	4.534e-7	1.02	0.3221
X2*X3	0.0000015	2.735e-7	5.47	<.0001
X3*X3	-5.873e-9	1.32e-9	-4.45	0.0004

Table 4-6 Preliminary Investigation. Summary of Fit for Air to Solids Ratio (Y3)

Summary of Fit for Y3

RSquare	0.983501
RSquare Adj	0.97319
Root Mean Square Error	0.217929
Mean of Response	1.40232
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	45.298159	4.52982	95.3784
Error	16	0.759890	0.04749	Prob > F
C. Total	26	46.058049		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-2.908098	1.397032	-2.08	0.0538
X1	0.0741062	0.034706	2.14	0.0486
X2	0.0435785	0.016899	2.58	0.0202
X3	-0.000024	0.000049	-0.48	0.6367
X1*X1	-0.000199	0.00025	-0.80	0.4381
X1*X2	0.0005249	0.000129	4.06	0.0009
X2*X2	-0.000085	0.000115	-0.74	0.4711
X1*X3	-0.000003	4.226e-7	-6.14	<.0001
X2*X3	-0.000002	2.549e-7	-8.63	<.0001
X3*X3	5.9218e-9	1.23e-9	4.81	0.0002

Table 4-7 Preliminary Investigation. Summary of Fit for Rise Rate (Y4)

Summary of Fit for Y4

RSquare	0.969194
RSquare Adj	0.94994
Root Mean Square Error	0.146296
Mean of Response	0.983704
Observations (or Sum Wgts)	27

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	10	10.773588	1.07736	50.3377
Error	16	0.342442	0.02140	Prob > F
C. Total	26	11.116030		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-3.0054	0.93783	-3.20	0.0055
X1	0.0634292	0.023298	2.72	0.0151
X2	0.0448367	0.011344	3.95	0.0011
X3	0.0000304	0.000033	0.92	0.3705
X1*X1	-0.000346	0.000168	-2.06	0.0561
X1*X2	-0.000165	0.000087	-1.90	0.0755
X2*X2	-0.000069	0.000077	-0.90	0.3840
X1*X3	-5.296e-7	2.837e-7	-1.87	0.0804
X2*X3	-1.189e-7	1.711e-7	-0.69	0.4973
X3*X3	4.427e-10	8.26e-10	0.54	0.5993

Air to solid ratio (Y3) (Table 4-6) depended on air pressure (X1) (Prob = 0.0486), recycle rate (X2) (Prob = 0.0202), and the interaction between air pressure (X1), recycle rate (X2), and the initial solids concentration (X3) (X1X2, X1X3 and X2X3). Rise rate (Y4) (Table 4-7) depended mainly on air pressure (X1) (Prob= 0.0151) and recycle rate (X2) (Prob= 0.0011).

The terms that are not significant for any of the response variables were: square air pressure (X1X1) and initial solids concentration (X3). However, initial solids concentration (X3) was included since it is involved interacting with the other parameters, thus the hierarchy in the model is conserved. Using a contour profiler and defining the ranges for the values of the response variables, according with the literature, an area of operation was defined.

It has been observed from the experimental data that the effluent suspended solids (Y1), cannot reach levels that comply with the normal final discharge standards (30 mg/l). The final effluent quality was expected to not comply with the standards and the system was expected to be a pretreatment before treating the effluent in a conventional activated sludge plant. For this reason the effluent quality was set at a maximum of 300 mg/l (5.7 in Ln scale). Percentage of Solid Recovery (Y2) was set as a minimum of 95%, according with the literature. Values lower than 95%, in a typical solid-liquid separation using DAF unit is considered a not efficient performance, although in this research subnatant suspended solids was a more important control parameter. Air to solid ratio (Y3) should be minimized to control operating costs. Another reason to minimize this ratio is to reduce the amount of air used to reduce turbulence inside of the flotation tank. Therefore the shear forces acting on the surface of the floc structure are minimized, keeping the particle-bubble aggregate together. Rise Rate (Y4) usually varies from 0.22 to 4.5 GPM/ft^2, according with the typical values supplied by the manufacturers of DAF units.

The results from the analysis reveal two possible areas for complying with the optimization of the DAF unit (Figure 4-2). The area that defines the region of low pressure and medium recycling percentage corresponds to the best solution. The selection of this area as best solution, because lower operational pressures result in smaller volume to compress, which leads to an economy of energy. The other area uses a higher recycling volume that would require more energy for compressing the air that would increase the operational cost and the construction cost for the DAF unit. At the same time, high values for recycling ratio may cause turbulence inside of the flotation tank, which can destroy the floc structure, affecting the efficiency of the treatment.

The data analysis and the graphical representation shown in the contour profiler lead to the conclusion that the ranges for operational values at the preliminary investigation were set between 40-60 psi for air-pressure and between 30-50 % for the recycle ratio.

According with ranges defined in the preliminary investigation, a new analysis was performed. The current investigation was focused on this specific area of operation. In this way the optimal ranges of operation for performing a solid-liquid separation using dissolve air flotation will be defined.

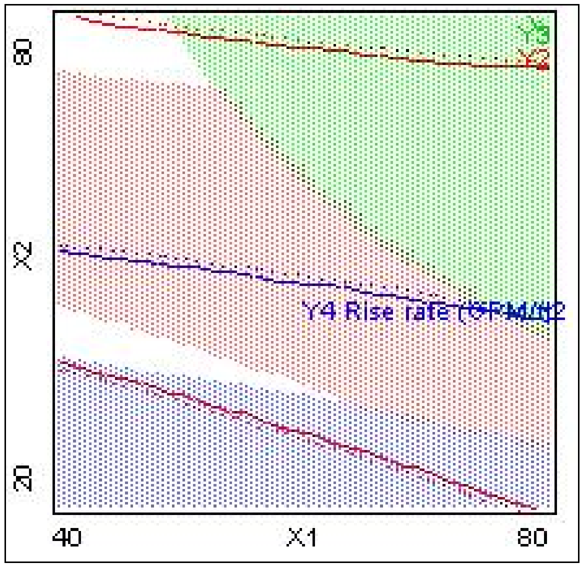


Figure 4-2 Contour Profiler. Preliminary Investigation

4.3.2 Current Investigation

With the preliminary ranges for the operational parameters defined, an expanded DAF test program was performed. Data obtained was shown in Table 4-3. In a first step to determine the significant parameters involved in the process a statistical analysis was performed. Using a significance α = 0.05 parameters not influencing the performance of the treatment were screened out. Results of the statistical analysis are shown in Tables 4-8, 4-9, 4-10, and 4-11.

From the results shown in the tables mentioned above it is possible to observe from the summary of fit for every response variable that the RSquare value is higher than 0.82. This value indicates that data obtained will not need major corrections, thus the level of confidence on the analysis is high.

Table 4-8 Current Investigation. Summaries of Fit for Solids in Subnatant (Log Y1)

Summary of Fit for Log (Y_1)

RSquare	0.852647
RSquare Adj	0.80164
Root Mean Square Error	0.200352
Mean of Response	5.76888
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	6.0390928	0.67101	16.7163
Error	26	1.0436672	0.040141	**Prob > F**
C. Total	35	7.08276		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-1.922949	4.490591	-0.43	0.672
X1	-0.0006	0.078504	-0.01	0.994
X2	0.2416761	0.067693	3.57	0.0014
X3	0.0005955	0.000715	0.83	0.4126
X1*X1	-0.000485	0.000708	-0.69	0.4994
X1*X2	0.0018733	0.000501	3.74	0.0009
X2*X2	-0.004779	0.000708	-6.75	<.0001
X1*X3	-2.66E-06	2.83E-06	-0.94	0.3564
X2*X3	8.29E-06	2.83E-06	2.93	0.007
X3*X3	-4.36E-08	3.38E-08	-1.29	0.208

Table 4-9 Current Investigation. Summaries of Fit for Solids Recovery (Y2)

Summary of Fit for Y_2

RSquare	0.825518
RSquare Adj	0.765121
Root Mean Square Error	0.740557
Mean of Response	96.22222
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	67.463186	7.49591	13.6681
Error	26	14.259036	0.54842	**Prob > F**
C. Total	35	81.722222		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	129.95482	16.59845	7.83	<.0001
X1	-0.039699	0.290172	-0.14	0.8922
X2	-1.030379	0.250211	-4.12	0.0003
X3	-0.002712	0.002644	-1.03	0.3145
X1*X1	0.0018333	0.002618	0.7	0.49
X1*X2	-0.00575	0.001851	-3.11	0.0045
X2*X2	0.0150833	0.002618	5.76	<.0001
X1*X3	7.24E-06	1.05E-05	0.69	0.4957
X2*X3	2.05E-06	1.05E-05	0.2	0.8461
X3*X3	1.37E-07	1.25E-07	1.1	0.282

Table 4-10 Current Investigation. Summaries of Fit for Air to Solids Ratio (Y3)

Summary of Fit for Y3

RSquare	0.992321
RSquare Adj	0.989662
Root Mean Square Error	0.040671
Mean of Response	1.180255
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	5.5572062	0.617467	373.2962
Error	26	0.0430065	0.001654	**Prob > F**
C. Total	35	5.6002127		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	-6.519959	0.911569	-7.15	<.0001
X1	0.0225525	0.015936	1.42	0.1689
X2	0.0076284	0.013741	0.56	0.5835
X3	0.0011987	0.000145	8.26	<.0001
X1*X1	0.000000075	0.000144	0	0.9996
X1*X2	0.0008359	0.000102	8.22	<.0001
X2*X2	-0.00000005	0.000144	0	0.9997
X1*X3	-0.00000237	5.751E-07	-4.12	0.0003
X2*X3	-0.00000209	5.751E-07	-3.64	0.0012
X3*X3	-5.276E-08	6.855E-09	-7.7	<.0001

Table 4-11 Current Investigation. Summaries of Fit for Rise Rate (Y4)

Summary of Fit for Y4

RSquare	0.828796
RSquare Adj	0.769533
Root Mean Square Error	0.161903
Mean of Response	0.583056
Observations (or Sum Wgts)	36

Analysis of Variance

Source	DF	Sum of Squares	Mean Square	F Ratio
Model	9	3.2992401	0.366582	13.985
Error	26	0.6815238	0.026212	**Prob > F**
C. Total	35	3.9807639		<.0001

Parameter Estimates

Term	Estimate	Std Error	t Ratio	Prob>|t|
Intercept	12.537346	3.6288	3.45	0.0019
X1	-0.032241	0.063438	-0.51	0.6156
X2	-0.150317	0.054702	-2.75	0.0108
X3	-0.001855	0.000578	-3.21	0.0035
X1*X1	-0.000304	0.000572	-0.53	0.5997
X1*X2	0.0018812	0.000405	4.65	<.0001
X2*X2	0.0001208	0.000572	0.21	0.8345
X1*X3	2.661E-07	0.000002289	0.12	0.9084
X2*X3	7.5873E-06	0.000002289	3.31	0.0027
X3*X3	7.6954E-08	2.729E-08	2.82	0.0091

As can be seen in Table 4-8 from the parameter estimates, suspended solid concentration in the subnatant (Y1) depended mainly on the recycle rate (X2) (Prob = 0.0014), as well as in its interaction with air pressure and the initial total solids concentration (X1X2, X2X3) (Prob = 0.0151 and (Prob = 0.007, respectively).

In the same way, percentage of recovery (Y2) (Table 4-9) relies on recycle ratio (X2) (Prob = 0.0003), and its interaction with air pressure (X1) (Prob = 0.0045). Since %R depends on suspended solid concentration in the subnatant (X3), this dependency with recycle ratio is correct. Air to solid ratio (Y3) (Table 4-10) depended on the initial solids concentration (X3) (Prob < 0.0001) and its interaction with air pressure and recycle ratio (X1X3 and X2X3) (Prob = 0.0003 and Prob = 0.0012, respectively). Rise Rate (Y4) (Table 4-11) depends on recycle rate (X2) (Prob = 0.0151), initial total solids (X3) (Prob = 0.0035), and the interaction between each of them and air pressure and recycle ratio (X1X2 and X2 X3) (Prob < 0.0001 and Prob = 0.0027, respectively).

Having the significant parameters identified and screening them out, a new analysis of the data was performed. In this run parameters which were not significant, were not included in the analysis. Now, correlations between the variables under study (air pressure, recycle ratio, and initial solids in the raw sludge) and the response variables (suspended solids in the subnatant, percentage of recovery, air to solid ratio, and rise rate) were determined. Figure 4-3 shows the results of this analysis. The black line in the middle represents the curve of the experimental data, and the blue lines represent the band of the expected values with a ± 5% respect the experimental data ($\alpha = 0.05$).

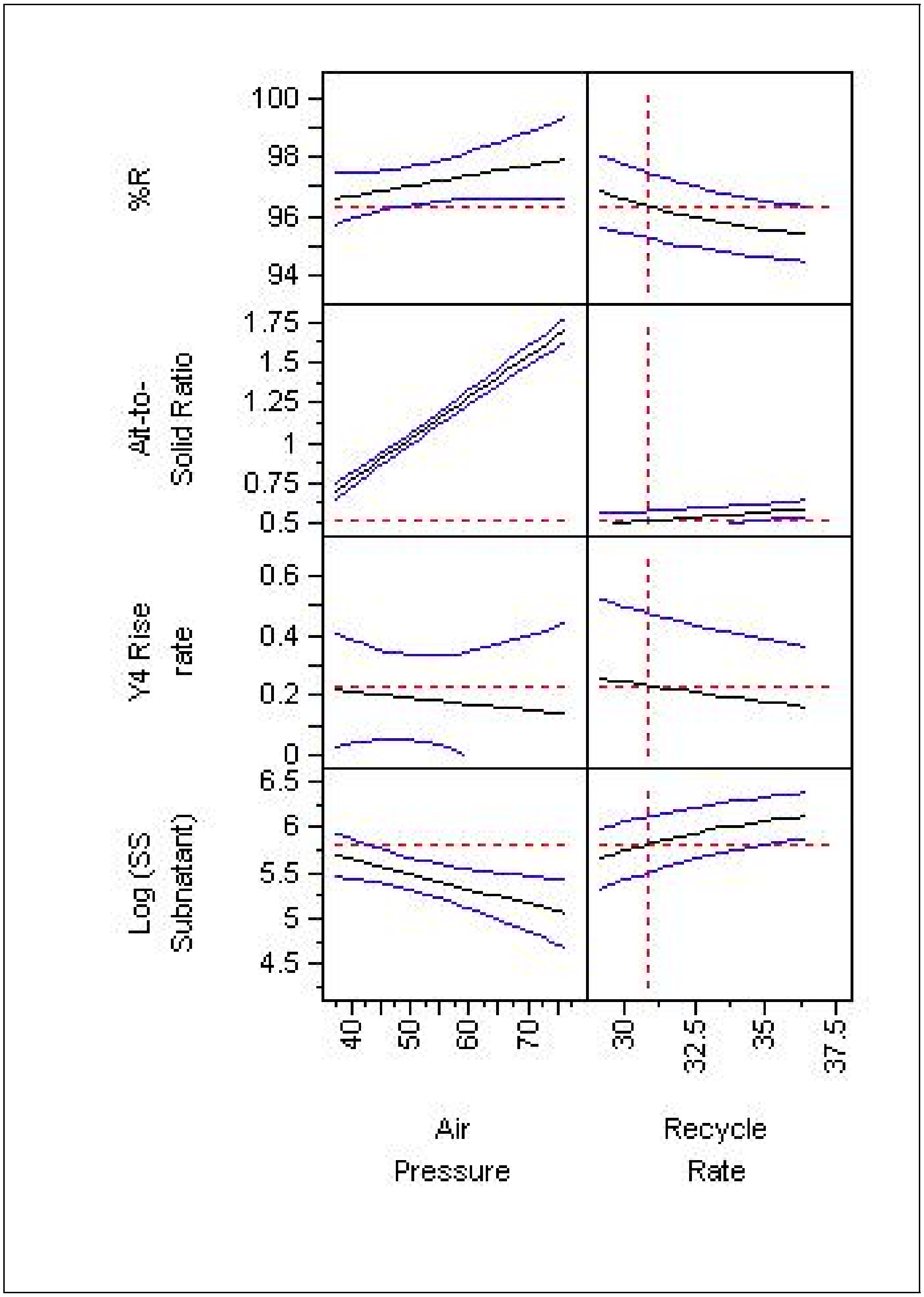


Figure 4-3 Current Investigation. Correlation Between Variables Under Study and Response Variables

As it can be seen in the previous figure air pressure has a linear correlation with the responses parameters. Suspended solids in the subnatant decrease while the air pressure increase, at fixed values of recycle ratio and initial solid concentration in the raw sample. This can be observed relating the fact that air to solid ratio and rise rate increase while the air pressure increase. The higher the air pressure applied in the system, the finer the air bubbles produced. Fine bubbles have a bigger surface of contact with the particles, making them become less dense, increasing the velocity of the particles rising to the surface. In this way a better quality of the effluents in the system can be achieve.

Recycle ratio has an opposite relationship with suspended solids in the subnatant. While the recycle ratio increase the concentration of suspended solids in the subnatant increase, decreasing the percentage of solids recovery in the system. When the recycle ratio is increasing, air to solid ratio and rise rate are increasing. This diminishing quality of the effluent is explained by the fact that high values in the recycle ratio produce turbulences inside of the flotation tank, affecting the floc structure. When turbulences occur, shear forces acting on the surface of the particle-bubble aggregate are high, tearing up the floc structure.

A similar analysis was performed using 3-D surface plots. The influence of air pressure and recycle ratio for each of the response variables was analyzed. Air pressure corresponds to the width of the cube; recycle rate to the depth and the response variables to the height.

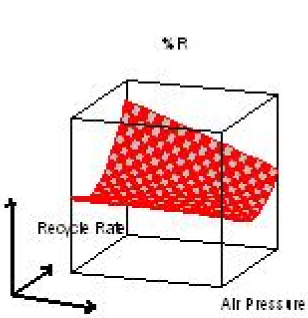
Values for air pressure and recycle rate in the surface plots range between 35-75 psi and 25-60 % respectively. For the response variables, typical values of operation for DAF units were used to scale the cubes. Table 4-12 show the typical values of the response variables in the typical operation of a DAF unit.

As it can be seen for solid recovery (Figure 4-4 a) the highest values were obtained when a low air pressure and a high recycle ratio was used. While the air pressure was increasing the solid recovery for high recycle rate was decreasing.

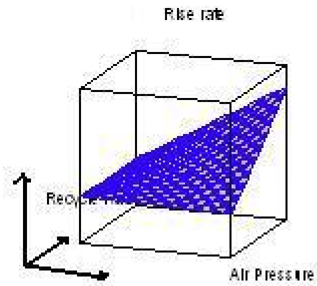
For rise rate (Figure 4-4 b) the highest values were obtained when a high air pressure and recycle rate were used. For low values of recycle rate, rise rate did not have a big response when the values for air pressure were increased. Air-to-solid ratio (Figure 4-4 c) showed the biggest response when high value of air pressure was used. This is because by increasing the air pressure the level of saturation of the recycle effluent is increased, therefore the air content in the flotation chamber will be higher. For the suspended solids in the subnatant (Figure 4-4 d) the response is similar to the one observed in Figure 4-4 a.

Table 4-12 Typical Values of Operation of a DAF Unit

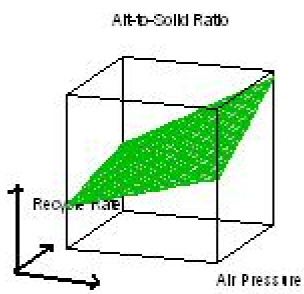
Parameter	Typical Value
Percentage of Recovery (%)	95-100
Rise Rate (GPM/ft^2)	0.22-4.5
Air-to-Solid Ratio (ml/L)	1.5 (max)



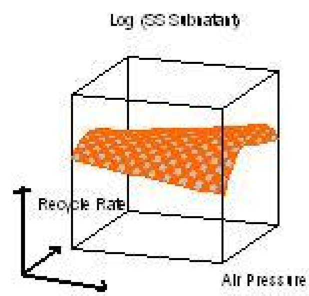
(a) Solid Recovery



(b) Rise Rate



(c) Air-to-Solid Ratio



(d) Log SS Subnatant

Figure 4-4 Surface Plots for Influence of Air Pressure and Recycle Rate over the Response Variables (Air Pressure ranges between 35-75 psi and Recycle Ratio ranges between 25-60%)

Highest values for solid recovery were obtained when low values of air pressure and high values of recycle rate were used, as a consequence the lowest values of suspended solids in the subnatant corresponded to the same area.

Once the correlations between the variables under study and the response variables were determined, contour profiles were generated in order to determine the optimal ranges of operations at certain conditions of operation. Again, typical values of operation of the response variables were used to determine the area of operation of the treatment. In a first analysis no limitation for the quality of the effluent on the system was set in order to determine the full ranges of operation of the controlling parameters. Ranges for the rest of the response variables recommend in the preliminary investigation were set within the same values.

As it can be seen in the contour profile (Figure 4-5) an extensive area of operation was determined. Ranges for the operational parameters were ranged between 35-70 psi for the air pressure and 30-60 % for the recycle ratio. It can be observed that while values for air pressure increase, values for the recycle ratio decrease, following the correlations determined in the statistical analysis. Since this treatment was not intended to be a final treatment a second contour profile was generated leaving the limits for the percentage of recovery open, to identify the influence of this parameter in the performance of the system.

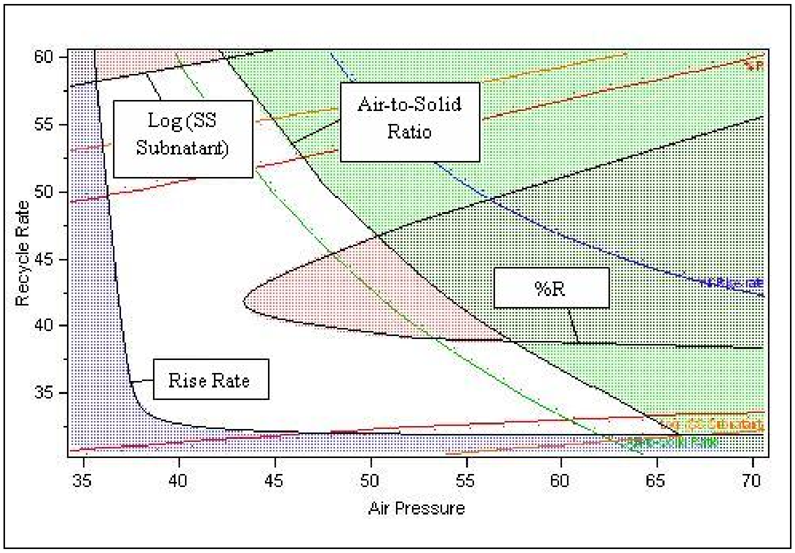


Figure 4-5 Current Investigation. Contour Profile without Limitation for the Quality of the Final Effluent

In Figure 4-6 can be observed that the area of operation (white area) had a slight variation when the percentage of recovery was set without limitations.

As a consequence it might be stated that percentage of recovery does not have a big influence on the area of operation of the system. This variation affects the area located for values of air pressure between 45-55 psi.

In a second analysis, the best quality possible to achieve with the treatment for the final effluent was tested. As mentioned in the preliminary investigation, values obtained for the suspended solids in the subnatant did not comply with the standard to be considered as final discharge (30mg/L). First, results for a successful treatment were obtained when the concentration of the suspended solids in the subnatant was set in 150 mg/L.

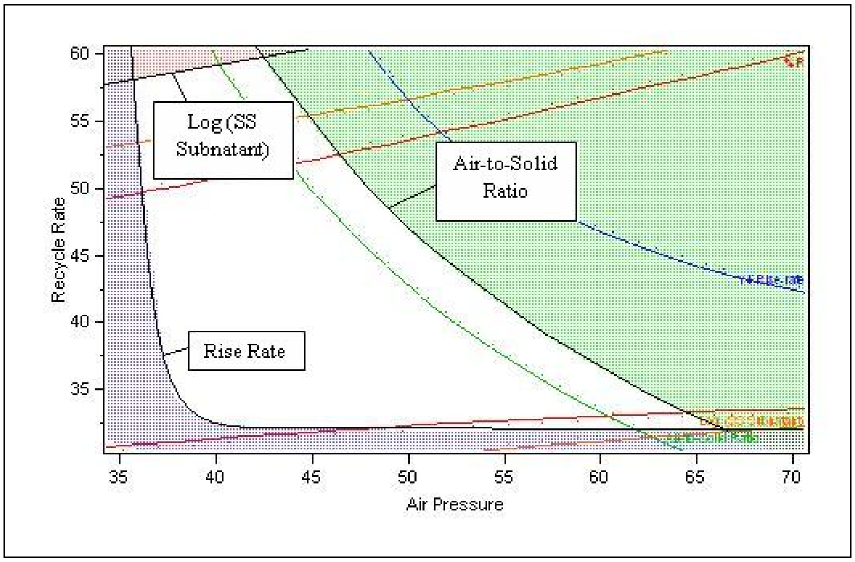


Figure 4-6 Current Investigation. Contour Profile without Limitation for the Quality of the Final Effluent and for Percentage of Recovery

For this value of the suspended solids concentration in the subnatant, values for air pressure and recycle ratio were ranged between 35-45 psi and 55-60 %, respectively. Results can be observed in Figure 4-7. Analogously, limits for percentage of recovery were left open to determine if there is an influence in the system performance.

As it can be seen in Figure 4-8, there is no variation in the area of successful treatment (white area) when the value for the concentration of the suspended solids in the subnatant was set in 150 mg/L. The area of influence identified in the first analysis does not affect the area of operation for this quality on the final effluent.

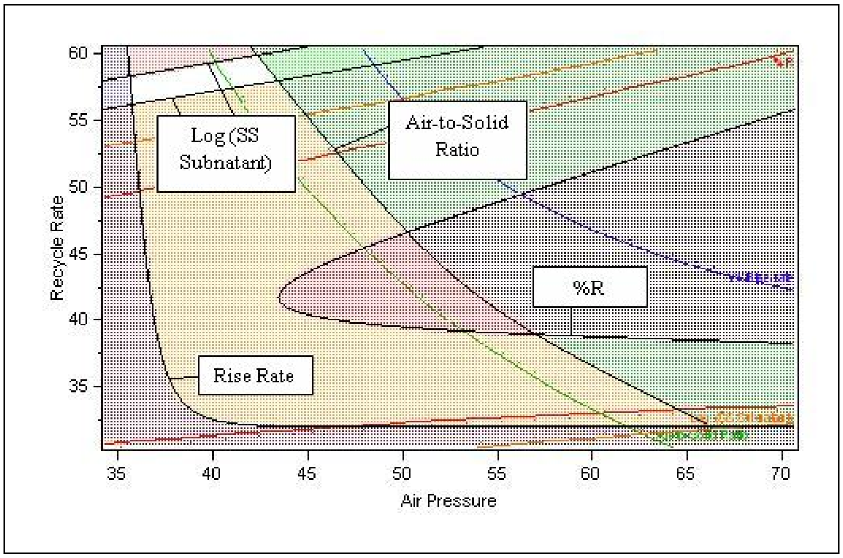


Figure 4-7 Current Investigation. Contour Profiler for concentration of suspended solids in subnatant set in 150 mg/L

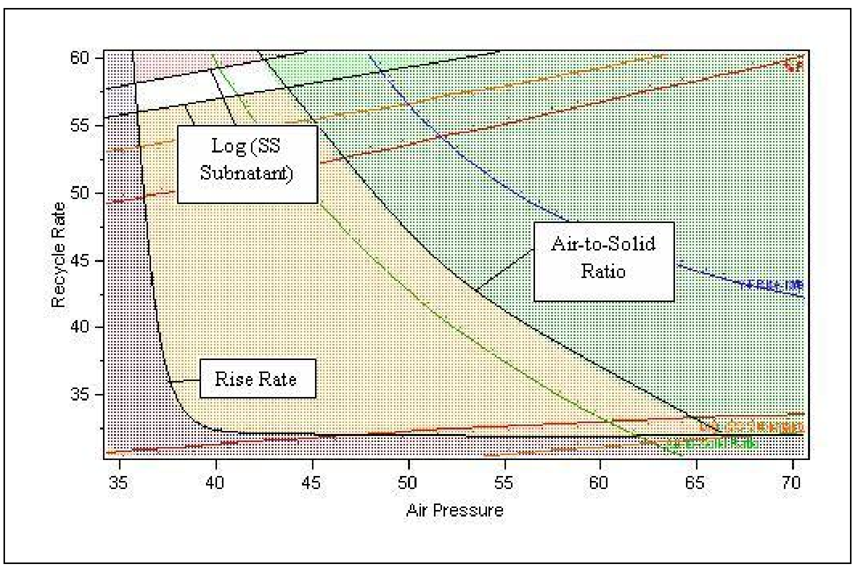


Figure 4-8 Current Investigation. Contour Profiler for concentration of suspended solids in subnatant set in 150 mg/L and no limits for the percentage of recovery

A final analysis was performed, in order to determine the optimal ranges for the controlling parameters to obtain a final quality of the final effluent of the system of 300 mg/L of suspended solids in the subnatant as a maximum. This concentration defines the limit for a successful treatment. As it can be seen in Figure 4-9 two areas of successful operation were found (white areas). The first one was located in the zone of high recycle rate and very low air pressure. The ranges for these parameters were 35-45 psi for the air pressure and 50-60 % for recycle rate.

The second one was located in the zone of low recycle rate. Ranges for the same parameters were between 45-70 psi and 30-35%, respectively.

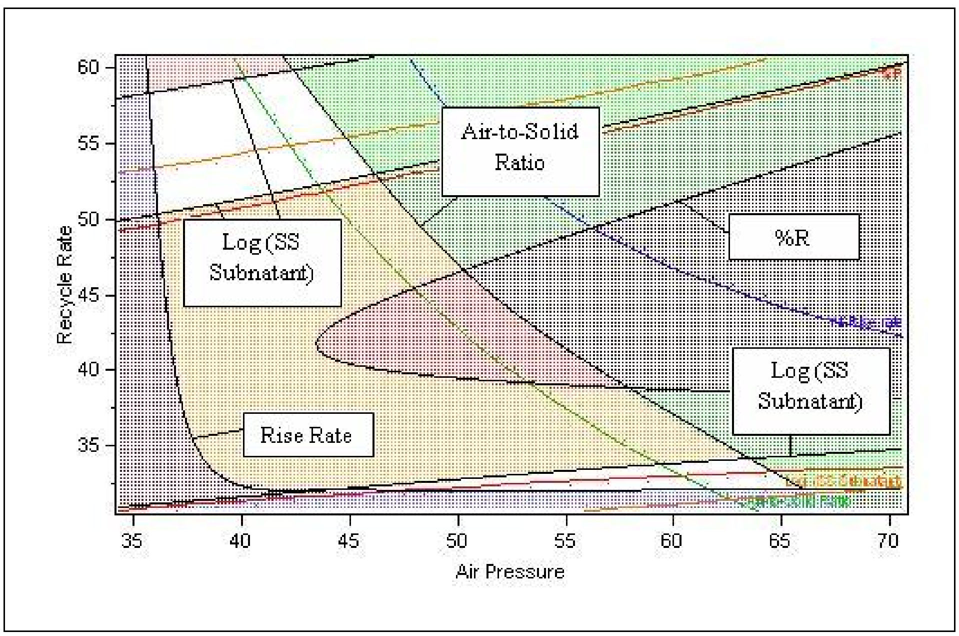


Figure 4-9 Current Investigation. Contour Profiler for concentration of suspended solids in subnatant set in 300 mg/L

When no limits for the percentage of recovery were set, the results for the ranges of successful treatment remained the same. Results for this case can be seen in Figure 4-10.

According to the results from the correlation analysis between variables under study and the response variables, the ranges for optimal operation of the controlling parameters which correspond to the best solution are the ones located in the area for low recycle ratio (30-35%) and medium-high low pressure (45-70 psi). This leads to the observation that when values for recycle ratio are increasing, values for the final concentrations in the suspended solids in the subnatant decrease, turning the treatment into a more expensive one and less efficient.

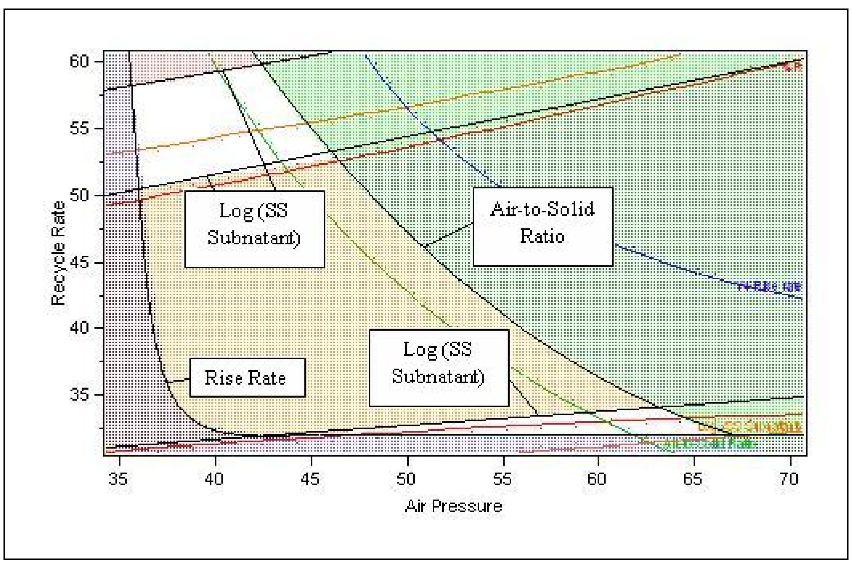


Figure 4-10 Current Investigation. Contour Profiler for concentration of suspended solids in subnatant set in 300 mg/L and no limits for the percentage of recovery

The higher the values for the recycle ratio, the bigger will be the pressurizing tank, and the higher will be the energy necessary to pressurize the recycle effluent, rising the costs of construction and equipments of the facilities. At lower values of recycle ratio, the prediction model showed that better quality on the effluent was possible to achieve.

According with the analysis performed, percentage of recovery does not represent a controlling parameter in the performance of a successful solid-liquid separation using dissolved air flotation when the treatment is intended to be applied as a preliminary treatment. In this specific case, when dissolved air flotation is applied to effluents from an aerobic treatment to treat grease wastes rich in filamentous bacteria, the controlling parameter corresponds to the final concentration of the suspended solids in the subnatant. As a summary, Table 4-13 shows the results obtained in the preliminary investigation and the current investigation. As it can be seen in the table, the recommended new values of operation work with higher air pressure values than the ones obtained in the preliminary investigation. For recycle ratio the results recommend lower values. As it was explained in section 4.3.2 (correlations between the variables under study and response variables), the higher the values for air pressure the lower will be the values for recycle ratio. Finally, Table 4-14 shows a comparison between the values for the operational parameters in a typical application of DAF and the values obtained in the current investigation. As it can be seen, the values obtained in the current investigation ranged within the typical ranges of operation of DAF. As a conclusion, in order to apply this treatment under the specific conditions of this study, no changes in the equipment are required.

Table 4-13 Comparison between Recommended Ranges for Air Pressure and Recycle Ratio in Preliminary Investigation and Current Investigation

Parameter	Preliminary Investigation	Current Investigation
Air Pressure (psi)	40-60	45-70
Recycle Ratio (%)	30-50	30-35

Table 4-14 Comparison between Typical Values of Operation of DAF and Values Obtained in the Current Investigation

Parameter	Typical Value	Current Investigation
Air Pressure (psi)	40-80	45-70
Recycle Ratio (%)	20-100	30-35%
Air to Solid Ratio (ml/L)	1.5	1.5
Rise Rate (GPM/ft^2)	0.22-4.5	0.5-2.10
Percentage of Recovery (5%)	95-100	93.1-99.3

CHAPTER V

CONCLUSIONS AND COMMENTS

5. Conclusions and Comments

Results and analysis of this project showed that the main parameter controlling the performance of Dissolve Air Flotation (DAF) performing a solid-liquid separation in an activated sludge treating grease wastes rich in filamentous bacteria was the final concentration of the suspended solids in the subnatant. This parameter will define the ranges of optimal operation of the air pressure and recycle ratio in the system in order to achieve a specific final quality of the effluent.

Differing from the traditional application of dissolved air flotation, percentage or solid recovery does not set a controlling parameter in the treatment. Since the treatment was intended to be applied as a preliminary treatment percentage of solid recovery did not affect the areas of successful treatment, focusing the attention exclusively on the goal concentration of the suspended solids in the final effluent.

Values of optimal operation for the air pressure obtained ranged between 45-70 psi. Since successful results on the treatment can be obtained with low pressure (45-50 psi), a further investigation can be done testing the application of air flotation using air pulses to perform the solid-liquid separation. Typical values for air pressure used in DAF, range between 40-80 psi. Air flotation using air pulses corresponds to a less expensive solution, which would reduce the cost of operation and construction of the facilities needed for the treatment.

Since the controlling parameter was determined to be the concentration of the suspended solids in the subnatant, the application of polymers and/or coagulants could improve the efficiency of the treatment. In the classical application of dissolved flotation improvements up to 5% has been demonstrated in the quality of the final effluents.

Finally, according with the values obtained on the experiments and the statistical analysis of the prediction model, the values recommended for air pressure (psi) and recycle ratio (%) to perform a solid liquid separation by dissolved sir flotation in an activated sludge rich in filamentous bacteria while treating grease wastes are 45-70 psi and 30-35%, respectively.

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